

AN EVALUATION OF BATTERY POWER SUPPLIES FOR ELECTRIC RAILGUNS

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Abstract

This paper describes an analytical feasibility study of the use of chemical storage batteries as the power supply for an electric railgun. The railguns studied are capable of accelerating 1 to 10 kg projectiles to 10 km/sec. Batteries were studied because they offer extremely high energy storage density although they operate at low voltage. Thus, an inductive store must be used to provide pulse compression and voltage magnification. The effect of using room temperature, cryogenic, and superconducting inductors was studied. In addition, segmented railguns were investigated to attempt to reduce rail losses and thus energy requirements. Based on the information available, battery mass is prohibitive for all but a ground based test bed. Use of cryogenic or superconducting coils greatly reduced the battery mass; however segmentation of the gun produced an insignificant decrease in battery mass.

Introduction

Because electric railguns do not possess the inherent limitations of chemical propellant guns and rockets, they have been the subject of considerable research¹. The parallel electrode railgun consists of a pair of stationary, parallel conducting rails and a conducting projectile. An energy source, capable of delivering very high current, is connected to the breech end of the rails, and the projectile is accelerated by the Lorentz force which results from the interaction of the projectile current with the magnetic field of the rail currents. To achieve high values of acceleration, a pulse of very high current, voltage, power, and energy is required from the power supply.

Chemical storage batteries have been proposed as a possible energy source for railguns because they store

very large amounts of energy in a relatively compact volume^{2,3}. However, batteries operate at low voltage producing unacceptably low current risetimes and thus cannot directly power a rail gun. An inductor can be used, as shown in Figure 1, to provide energy storage, pulse compression, and voltage magnification. Initially switches S1 and S2 are closed to charge the storage inductor L_0 through the circuit and inductor resistance R_0 . When the desired current level is reached, S2 is opened and the current is commutated into the rails.

The purpose of this study was to investigate the feasibility of using battery power supplies for rail guns. It was assumed that projectiles ranging from 1 to 10 Kg were to be accelerated to 10 Km/sec. In order to determine the amount of batteries required, it was necessary to first design the projectiles, choose the dimensions of the rail guns, and determine the required storage inductances as a function of circuit resistance. The required battery mass was then determined for a range of inductor time constants, first for a single stage gun, then for segmented guns. Additional details, results, and computer program listings are contained in reference 4.

Rail Gun Design

Projectile

The projectiles must be capable of withstanding the high acceleration of launching, must be stable during free flight at hypersonic velocity, and must have acceptable terminal ballistics. The projectile design used for this study was a modified version of one developed by Barber⁵. Basically it consisted of a conical tungsten forebody and an aluminum afterbody which transitions from the circular cross section of the cone to the square cross section of the bore of the rail gun. This design causes the center of gravity of the projectile to be located closer to the front than it would be for a single material cone.

Since the same shape was used for all of the projectiles, the gun bore became larger as the mass of the projectile increased, but was fixed for each value of mass. In addition the maximum stress allowed in the projectile was used to calculate the maximum allowable acceleration. Table 1 shows the bore size and maximum acceleration for several values of projectile mass.

It was assumed that a plasma arc would form behind the projectile and act as the armature. The arc voltage has been shown to vary almost linearly with length. The arc voltage was necessary to calculate the performance of the rail gun and is also shown in Table 1.

Rail Gun Parameters

Current. The discharge circuit of the rail gun is shown in Figure 2 where L' and R are the inductance gradient and resistance of the rails. The electromagnetic force on the projectile is $L'I^2/2$ and is also equal to the product of mass and acceleration. A value

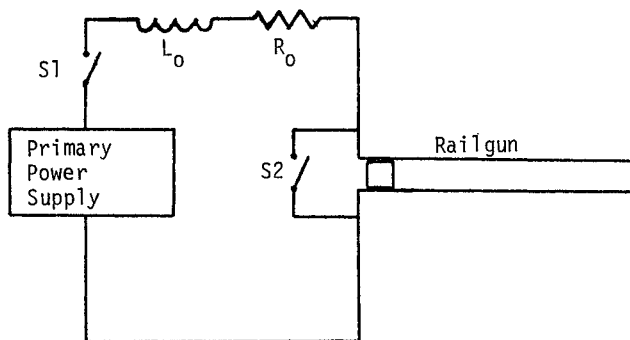


Figure 1: Railgun Equivalent Circuit During Charging

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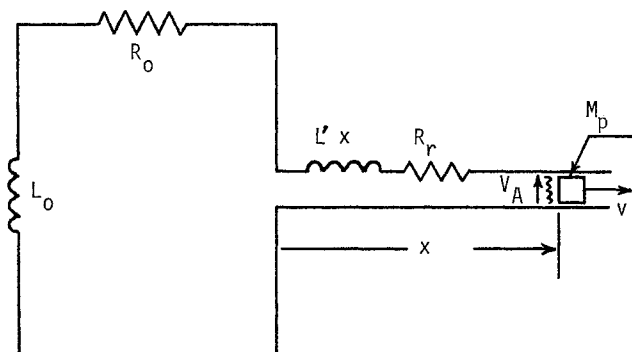


Figure 2: Railgun Equivalent Circuit During Launching

of $5\mu\text{H/m}$ was used for L' . Since the maximum acceleration was determined by the projectile design, the maximum allowable current can be calculated. This is the current which L_0 must be charged to and is shown in Table 1.

Rail Length. The minimum rail length was calculated by assuming the acceleration could be maintained at the maximum allowed value. The actual length, of course, must be longer since the current (and therefore the acceleration) drops as energy is removed from the storage inductor. In addition there is an important tradeoff between the rail length and the size of the storage inductance. This will be considered in more detail; however, the inductance must be at least large enough so that the stored energy ($L_0 I_0^2/2$) is equal to the kinetic energy of the projectile when it leaves the gun plus the energy lost in the system.

Storage Inductance. Barber derived a set of differential equations⁶ that describes the performance of the inductively driven rail gun. These equations consider the power circuit resistance, armature voltage and variation of the rail resistance as the current diffuses into the rails. A computer program was written to solve these equations for various values of L_0 , R_0 , and projectile mass. The length of the gun was determined by the position of the projectile when it achieved the required velocity.

Figure 3 shows the tradeoff between storage

inductance and gun length for a 1 Kg projectile in a single stage gun. Similar results were obtained for 4, 7, and 10 Kg projectiles except that values of inductance were larger. Clearly as the length of the gun is decreased the average acceleration must be increased. This requires a stiffer energy source, i.e., one with a larger inductance. The larger inductance stores more energy ($L_0 I_0^2/2$) which requires a larger power supply. Since the kinetic energy of the projectile at launching is constant, the overall efficiency (kinetic energy divided by total energy stored in L_0) is reduced. However a large amount of energy remains in the storage inductor at launch time and could conceivably be recovered. The percentage remaining increases as the gun length decreases. Conversely as the length increases, the storage inductance decreases toward a minimum value implying a smaller power supply and higher efficiency. In this case less energy remains in the storage inductor and more is dissipated in the resistances of the power supply and rails. Finally, increasing R_0 requires a larger L_0 since the losses increase.

Single Stage Gun Performance

In order to calculate the required battery mass

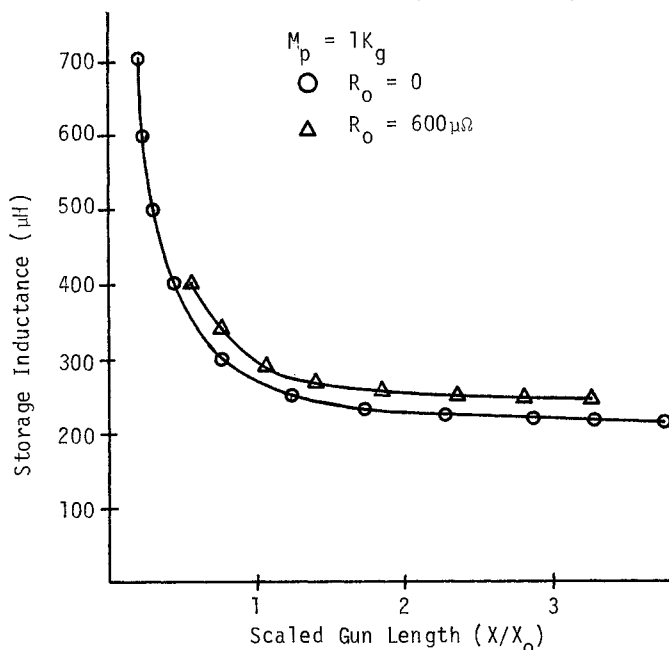


Figure 3: Storage Inductance vs. Scaled Gun Length

Table 1: Summary of Projectile and Rail Gun Parameters

| | Projectile Mass (kg) | | | | | | | | | |
|--|----------------------|------|------|------|------|------|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Rail Height (cm) | 3.25 | 4.09 | 4.68 | 5.15 | 5.55 | 5.89 | 6.21 | 6.49 | 6.75 | 6.99 |
| Allowable Acceleration ($10^5 \frac{\text{m}}{\text{s}^2}$) | 4.79 | 3.80 | 3.32 | 3.02 | 2.80 | 2.64 | 2.50 | 2.39 | 2.30 | 2.22 |
| Minimum Gun Length, x_0 (m) | 104 | 132 | 151 | 166 | 179 | 189 | 200 | 209 | 217 | 225 |
| Armature Voltage (V) | 650 | 820 | 940 | 1030 | 1110 | 1180 | 1240 | 1300 | 1350 | 1400 |
| Initial Gun Current, I_0 (MA) | 1.38 | 1.74 | 2.00 | 2.20 | 2.37 | 2.52 | 2.65 | 2.77 | 2.88 | 2.98 |

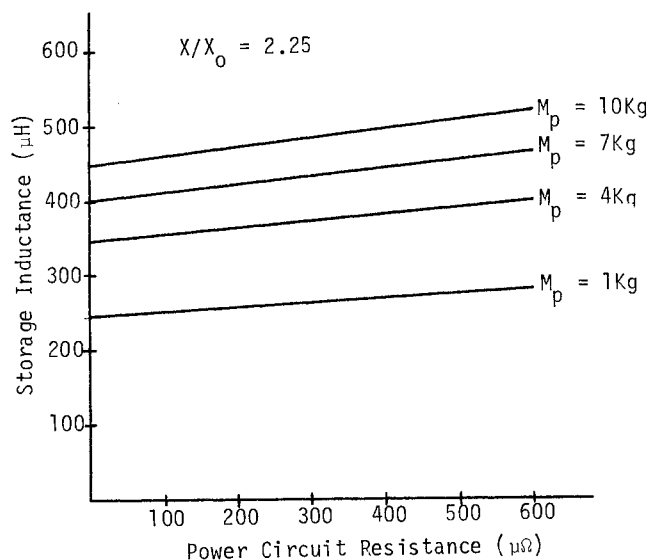


Figure 4: Storage Inductance vs. Power Circuit Resistance

for the power supply, it became necessary to choose a gun length. A scaled gun length (actual length divided by minimum gun length) of 2.25 was chosen as a compromise between L_0 and length. Using a constant scaled gun length allowed the calculation of L_0 as a function of R_0 and projectile mass. These results are shown in Figure 4. Note that L_0 and R_0 are linearly related.

Simulations were run for a number of combinations of resistance and inductance and included current as a function of time and detailed energy balance calculations. It was found that about 20% of the stored energy goes to the projectile while about 30% goes to heat the rails. In an attempt to reduce the rail losses and thus the power supply requirements, segmented rail guns were investigated.

Segmented Rail Gun Performance

One way of reducing the rail heating losses is to divide the gun into segments each with its own power supply. Segmenting a rail gun reduces rail losses by reducing the rail length that carries current at any one time, thus allowing inductive energy to be usefully applied along the length of the gun rather than being dissipated in the rails. Offsetting this advantage are timing and switching difficulties which will not be addressed here⁴.

Segmented guns were analyzed assuming that the scaled gun length of 2.25 was maintained, and that each segment would be identical (length, storage inductance, etc). The main change in analyzing the segmented gun is that the initial velocity for all stages after the first must be included. A program was written to solve the equations of operation to find the value of storage inductance (per stage) which yielded the proper exit velocity at the end of the final stage. As expected, the total storage inductance (no. of segments times the inductance per segment) was found to decrease as the number of segments increased. The storage inductance per stage was also found to be linearly related to the resistance per stage. From the curves of Figure 4 and similar results for the segmented guns, the inductance per stage was expressed as a function of the resistance per stage, i. e.

$$L_0 = AR_0 + B \quad (1)$$

where A and B are constants for a given projectile mass and number of gun segments. This equation was used for analysis of the power circuit.

Power Supply

Storage Inductor

In the analysis of the launching circuit, it was found that the storage inductance was a linear function of the power circuit resistance. Since the objective of this study was to determine the feasibility of battery power supplies, no attempt was made to actually design the storage inductor. Instead an approximate approach was used to yield a range of time constants (L_0/R_0) for each type of coil design (room temperature, cryogenic, and superconducting). Specifying the time constant allows one to solve equation (1) for the values of L_0 and R_0 provided the time constant is greater than the constant A.

The inductor will undergo a temperature rise during charging which would increase the coil resistance. For this study, the time constant was assumed to remain at its initial value during the entire charging period. This yields more efficient charging than would actually occur and thus somewhat optimistic battery requirements for the room temperature and cryogenic coils. Since the temperature of a superconducting coil is constant, its battery requirements would not be affected by this assumption.

Time constants of 0.25, 0.5, and 1.0 seconds were assumed to cover practical room temperature coil designs. Time constants for cryogenic coil designs were estimated by assuming that the same coil used for room temperature would be immersed in a pool of cryogenic fluid (liquid nitrogen or hydrogen). This would lower the initial temperature and resistance and increase the coil time constant. In addition there would be some heat transfer from the coil to the fluid during charging which would reduce the temperature rise. Thus the battery requirements for cryogenic coils should be less optimistic than for the room temperature coils. The resistivity of copper at the temperature of liquid nitrogen is 15% of its value at room temperature, while the resistivity of aluminum at the temperature of liquid hydrogen is 0.2% of its value at room temperature. Thus the respective time constants for copper coils in liquid nitrogen are 1.7, 3.3, and 6.7 seconds while those for aluminum coils in liquid hydrogen are 125, 250, and 500 seconds. The superconducting coil has zero resistance and therefore an infinite time constant.

Battery Model and Choice

The authors of reference 7 state that, "Although several battery systems, such as the lead-acid and nickel-iron systems, are among the oldest electrical devices..., analytical models of these batteries were surprisingly immature...in the late 1960's." Their interest was for electric vehicles; however, the same statement would still seem to apply to pulse applications. Several models⁷ are described, but the authors point out they often require experimental data which may not exist. Such was certainly the case for this study. Thus the battery was represented by the "universal model" which consists of an open circuit voltage source and a pulse battery equivalent series resistance.

The batteries chosen must supply extremely high current to the railgun. A survey of existing batteries showed that submarine batteries have, by far, the greatest current capabilities. The highest current

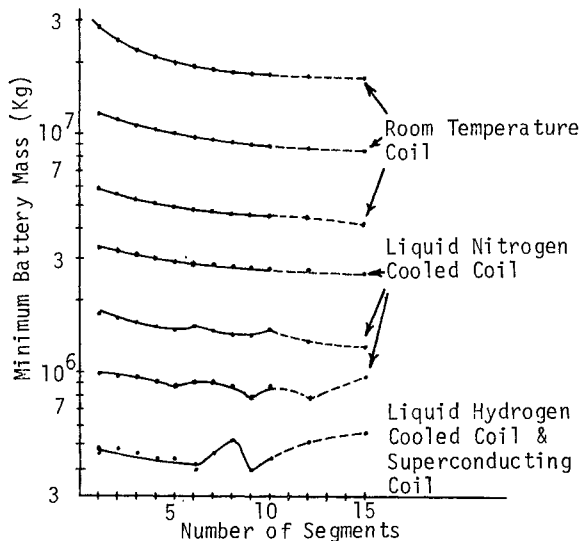


Figure 5: Minimum Battery Mass vs. Number of Segments (1 Kg Projectile, Various Coil Types)

battery found was the C&D Type SCC-57 and it was chosen for this study.

The cell contains lead-calcium alloyed grids, occupies a volume of 0.355 cubic meters (12.5 cu ft), weighs 982 Kg filled, and has been tested at high discharge rates. When shorted with approximately $20\mu\Omega$ of external resistance, the cell delivered 65 KA for about 5 secs at which point the test was terminated. It is believed the cell could deliver 65 KA for 10 secs without damage. From these results, the cell was modeled by a 2 volt source in series with a $10.6\mu\Omega$ pulse resistance. In addition, the maximum allowable cell current during the charging simulations was fixed at 65 KA. This operating condition corresponds to a power density (delivered to the load) of 86.8 W/Kg which compares favorably to the 100 W/Kg suggested for 1980 technology⁷.

Charging Circuit Analysis

The charging circuit consists of an $m \times n$ array of battery cells (where m and n are the number in series and parallel respectively), the storage inductance, and the power circuit resistance. A computer program was written to solve for the minimum battery mass for a given projectile mass, storage coil time constant, and number of segments. Figure 5 shows required battery mass vs number of segments for a 1 Kg projectile with coil design as a parameter. Dashed lines indicate that solutions were not obtained for every value of N (the number of segments). Figure 6 shows the minimum battery mass vs projectile mass for one and ten stage guns assuming the use of a superconducting coil. The masses shown are strictly those of the battery cells and do not include racks, interconnecting hardware, etc.

Conclusions

The objective of this study was to determine the feasibility of battery power supplies for rail guns. From the results obtained, several conclusions may be drawn.

First, the battery system mass (based on available data) is prohibitive, except possibly for a ground based test bed. Even there, the complexity and maintenance requirements might outweigh any advantages such as the availability of surplus batteries. Further testing of batteries in pulse type operation would be desirable since higher power densities would reduce

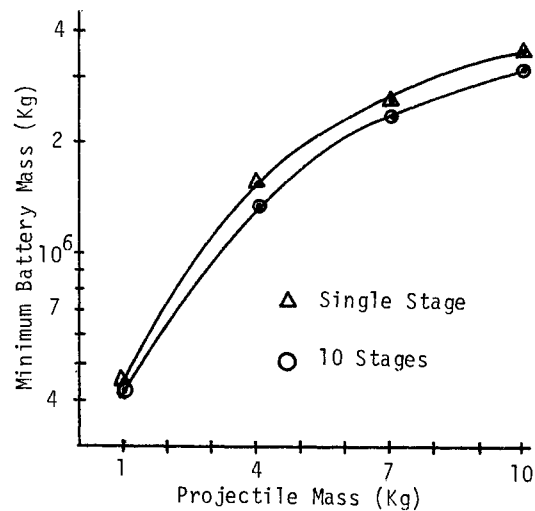


Figure 6: Minimum Battery Mass vs. Projectile Mass (Superconducting Coil)

the system size.

Second, segmentation of the gun generally reduces battery mass, but not enough to offset the added complexity.

Third, the added complexity of cryogenic or superconducting coils would appear to be justified by the very large decrease in battery mass.

Finally, the projectile design has a major impact on the system design regardless of the power supply. The maximum acceleration for the projectile designs used in this study resulted in very long gun lengths. Further research is required to design large projectiles which could withstand higher accelerations.

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